The Tevatron-to-LHC Physics Roadmap

Konstantin Matchev

University of Florida

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Conclusions

Borrowed liberally from the organisers' charge

- The era of undisciplined theorizing is over

What can you do for the LHC/Tevatron
and what can they do for you?

- There is a big gap between what even the phenomenologically oriented theorists are doing and
  - what the experimentalists need to do for TeV/LHC searches
  - what the experimentalists would like them to be doing
- The Tevatron can be useful and even complement the LHC
  - train the people
  - assemble the tools (analysis techniques, software)
  - provide some physics results
    - ∗ Bread and butter physics
    - ∗ Tevatron-friendly physics
    - ∗ Complementary physics

Typical phenomenologist's job

- Cook up new model (new particles, lots of parameters).
- Compute total cross-sections.
- Speculate on the spectrum and discuss possible signatures.
- Constraints from precision data.
- Constraints from similar collider searches.
- Simulations?
- Backgrounds?
- Optimize cuts?
- Discriminate from other models?

Signature based approach

- The need for model independence
  - there are many models, some have similar signatures
  - you never know what I will come up with tomorrow...
  - helps identify the salient features of the model
- Luminosity ain't cheap!
  - what can the LHC do with a limited data set?
    what if 1LHCyr=1 fb^{-1}?
  - build new lampposts (beyond the standard benchmarks?)
  - HW: find the most Tevatron-friendly SUSY model and advertise it to your CDF/D0 friends.

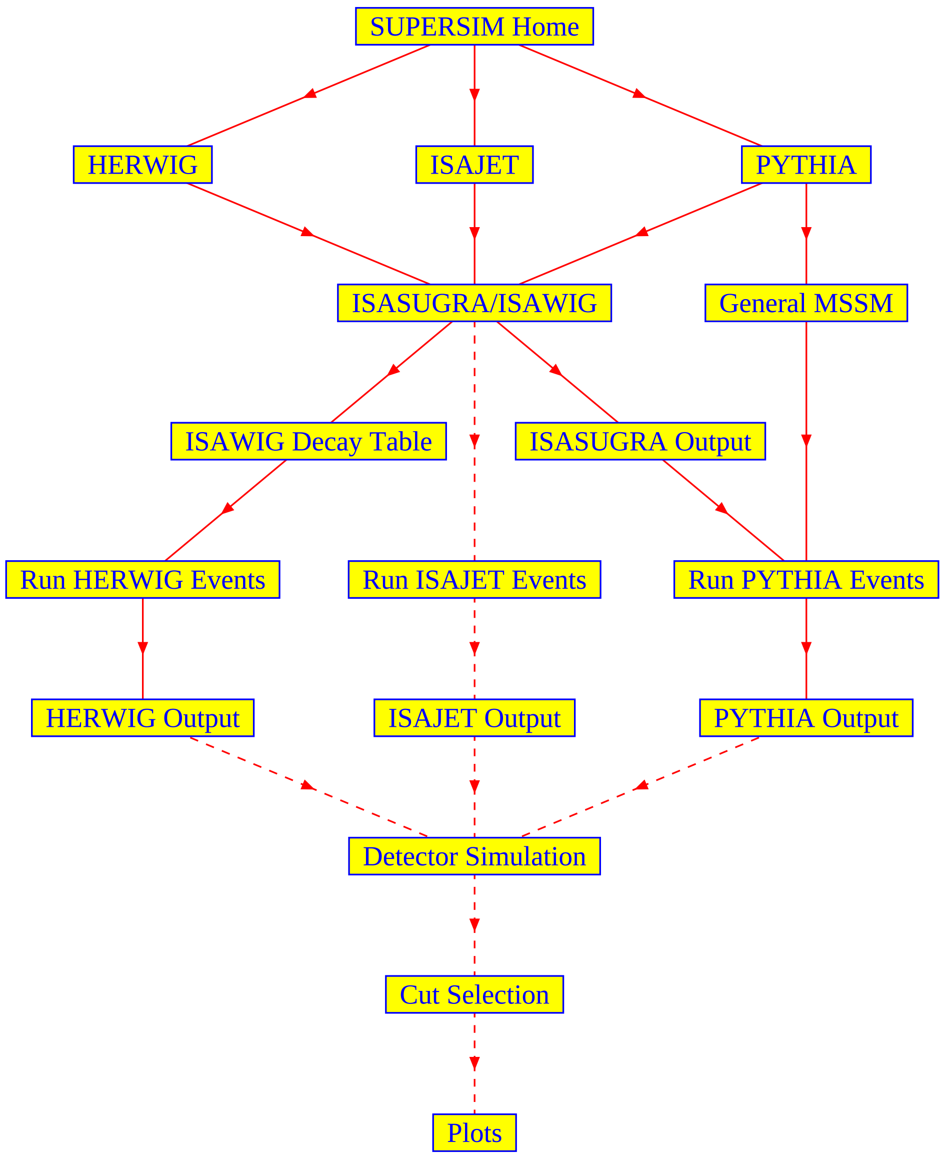
Event generators need a facelift

- There is a proliferation of new models on the market.
- Typical general purpose event generator has $2 \to 2$ processes. This may not be sufficient at the LHC (depending on the signature). $2 \to 3$, $2 \to 4$?
- Facilitate the interface between parton-level calculators and general purpose event generators (see Les Houches Accord).
- Think about overcoming current limitations:
  - add NLO corrections where necessary
  - in CompHEP: $N_f < 5$, no gravitons
  - implement spin correlations
  - improve user friendliness
  - think about theory uncertainties (pdfs? higher orders?) – important for backgrounds as well as potential discoveries
  - ... (homework: think of the most annoying feature / deficiency of the event generator you are currently using and let the conveners of your working group know)

Event generators for dummies

http//www.phys.ufl.edu/supersim

- SUPERSIM flow chart (Blender,Group,KM)



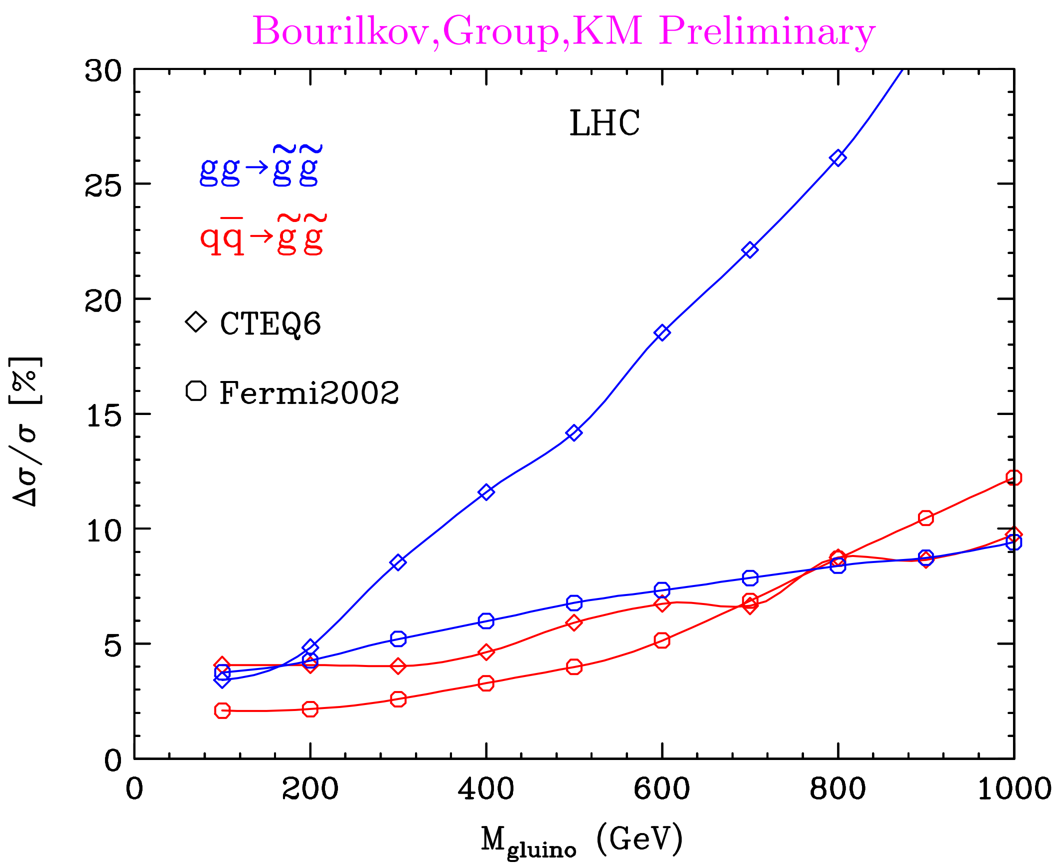
Studies of PDF uncertainties

Bourilkov,Group,KM 2004

- Goal: provide a tool for estimating the PDF uncertainties in Higgs and new physics processes at the Tevatron and the LHC.
- Interesting in its own right, but also necessary to make the connection between the Tevatron discoveries and/or measurements of SM backgrounds to the LHC.
- The LHAPDF interface (by now v.3) works with pdf sets
  - Fermi2002
  - CTEQ4-6
  - MRST2001-2003
  - Alekhin2002
  - Botje
  - ZEUS2002
  - H12000
  - GRV98
- LHAPDF has been interfaced with `PYTHIA` and `HERWIG`, `ISAJET` to come next.
- 100k events per pdf member on the UF CMS PC farm.

PDF uncertainties: gluino production

- Example: gluino production at the LHC

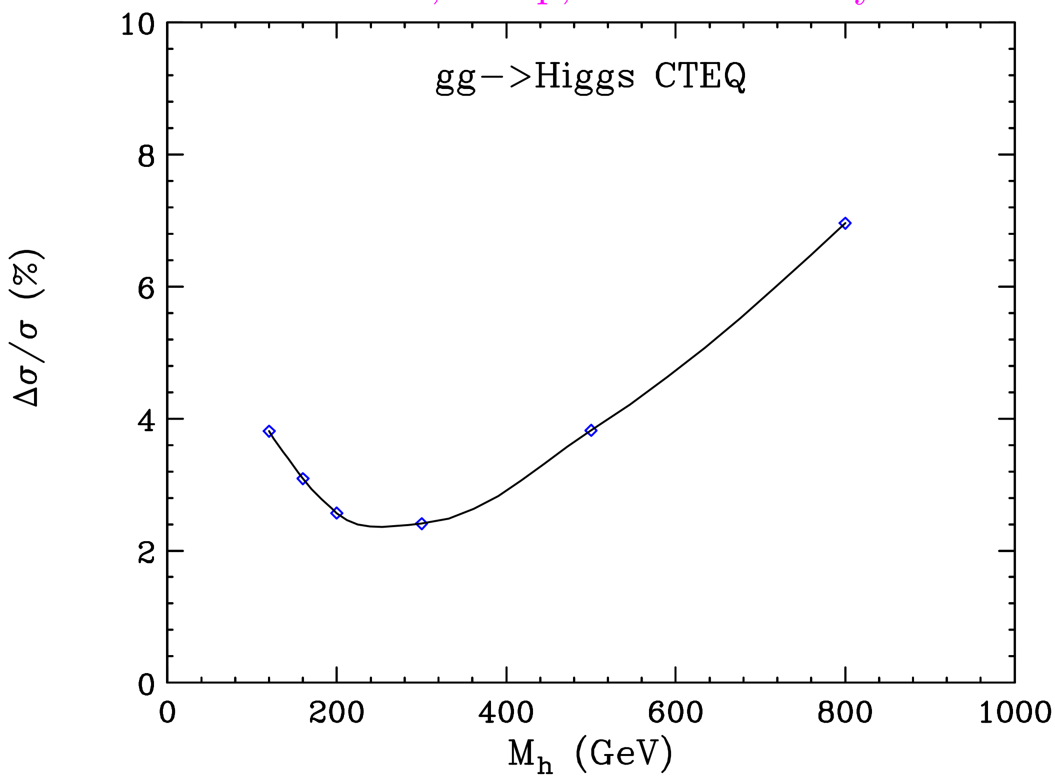


- $q\bar{q} \to \tilde{g}\tilde{g}$ agree (sort of)
- Large discrepancy in $gg \to \tilde{g}\tilde{g}$ (?)

PDF uncertainties

- Another example: $gg \to h$ at the LHC

Bourilkov,Group,KM Preliminary

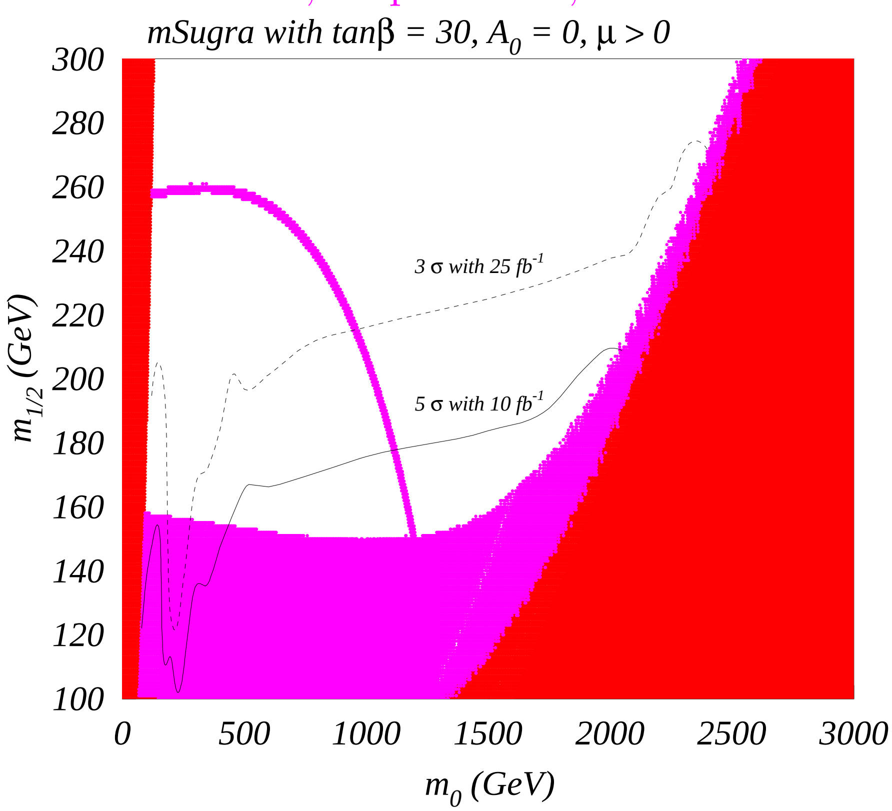


- It is interesting to study the uncertainty as a function of kinematic variables

Guaranteed physics: m_t, M_W

- Indirect constraints on new physics models
- Indirect constraints on $m_h \Longrightarrow$ top squark sector.
- 1 GeV at Tevatron is worth 1 TeV at LHC!
- MSUGRA parameter space with $m_t = 175$ GeV

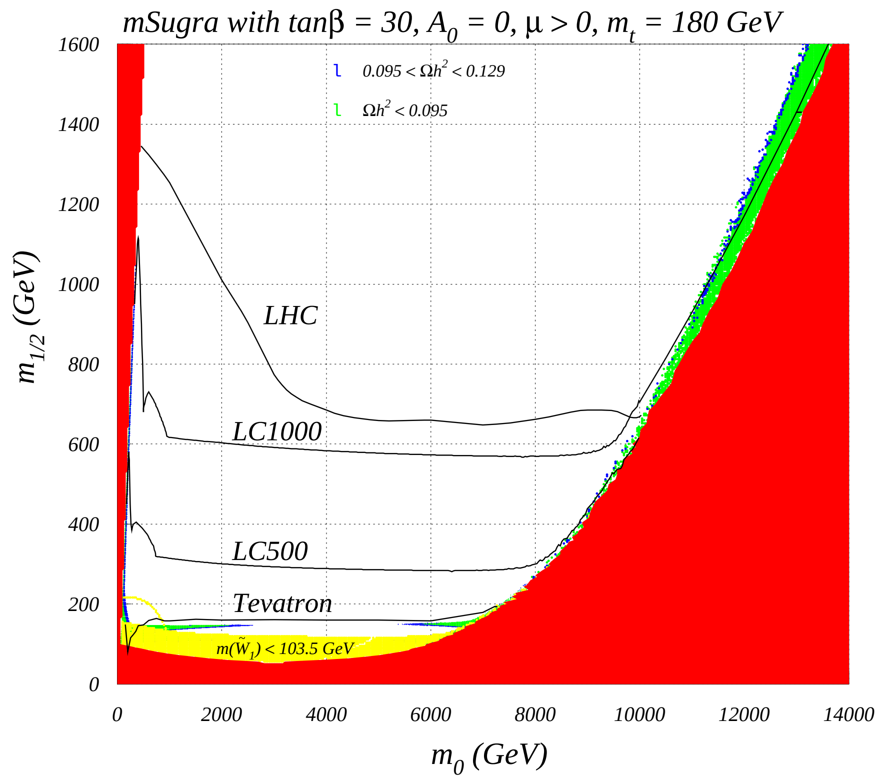
Baer,Krupovnickas,Tata



The effect of the top mass

- It looks very different for $m_t = 180$ GeV.

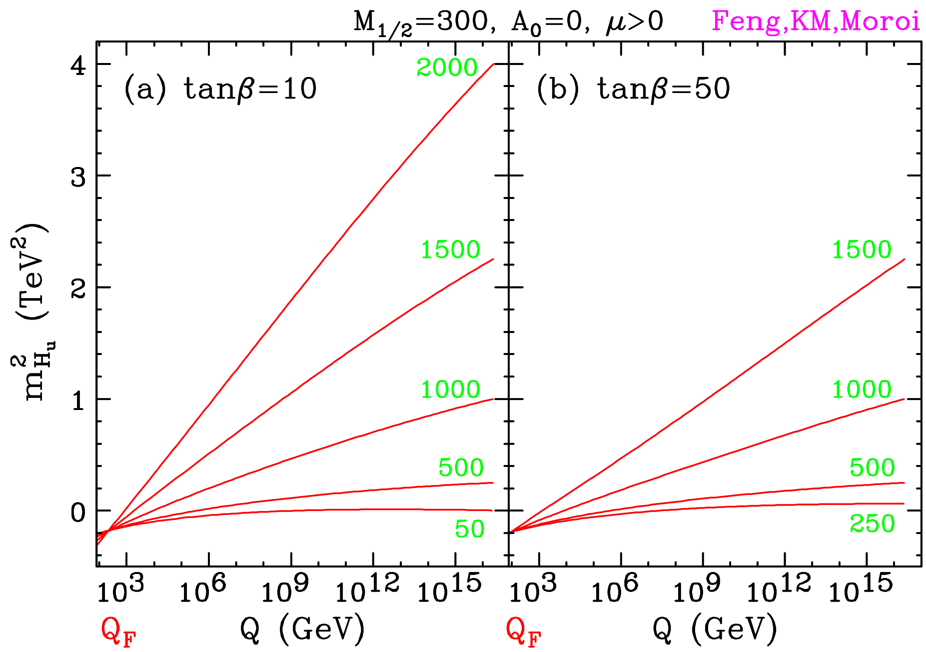
Baer,Krupovnickas,Tata



- For $M_{1/2} = 300$ GeV the FP region moved $2.5 \to 8.5$ TeV.
- Is this a big deal?

The other side of naturalness

- Focus point: natural from the top down. (Theorists cheer).

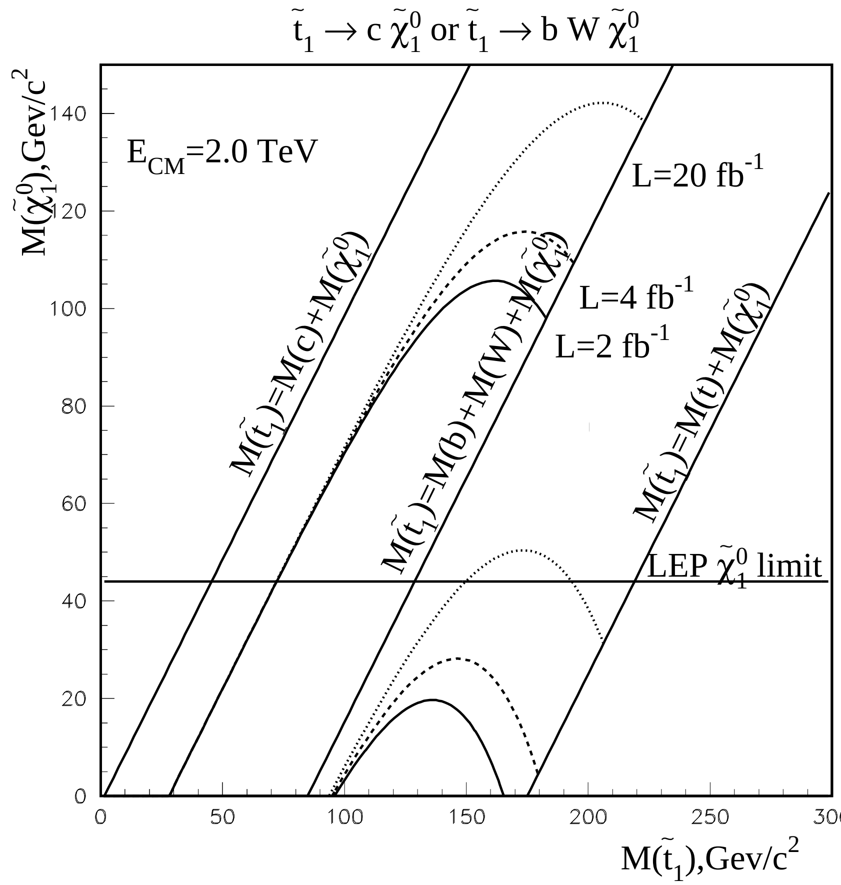


- Recall that $|m^2_{H_u}| \sim \mu^2 \sim m^2_{\tilde{h}}$.
- The RGE evolution of $m^2_{H_u}$ governed by $\lambda_t^2 \sim m_t^2$ and $m^2_{\tilde{q}}$.
- The need for experimental precision from the bottom up: we need to know m_t very well in order to extrapolate $m^2_{H_u}$ up to M_{GUT} and test SUSY unification.
- Redundancy in RGE programs is a good thing $\Longrightarrow$ "theory" error of the extrapolation.

Can the Tevatron beat the LHC?

- Light stop search in $\tilde{t}\tilde{t}^* \to c\bar{c}\not{E}_T$.

Demina,Lykkenov,KM,Nomerotski

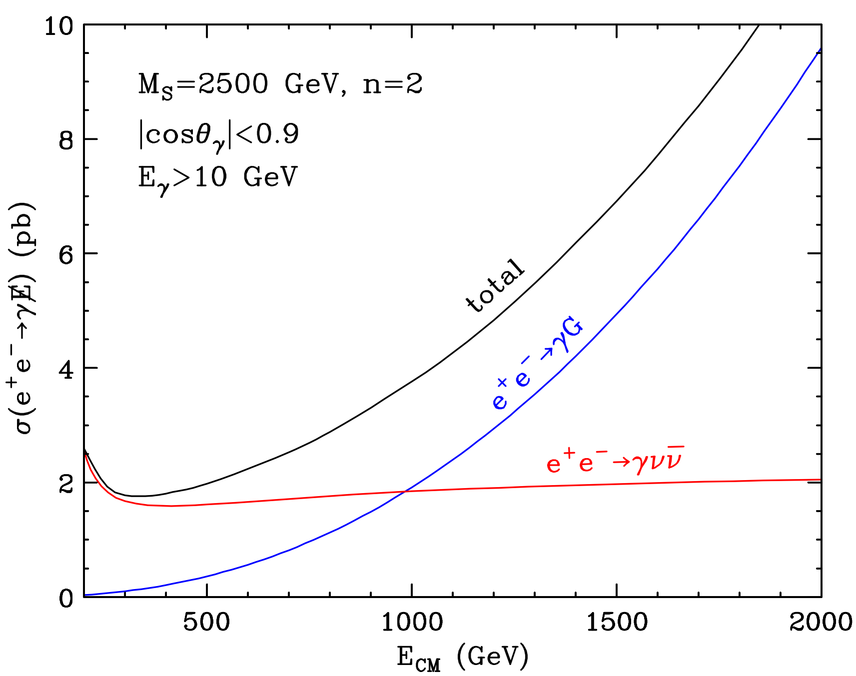


- It is a challenging signature in either case.
- If the stop is really light (see baryogenesis), the higher CM energy doesn't help. LHC plot?

Large Extra Dimensions (aka ADD)

- Real ADD gravitons in event generators. Until recently:
  - Run I: bootleg version of `PYTHIA` with graviton production as an external process (Lykken,KM, 1999)
  - `ISAJET` (Hinchliffe,Vacavant, 2000)
- The full ADD model now implemented in `AMEGIC++`.
  - Real graviton production
  - Virtual exchange (3 conventions)
  - New Feynman rules included

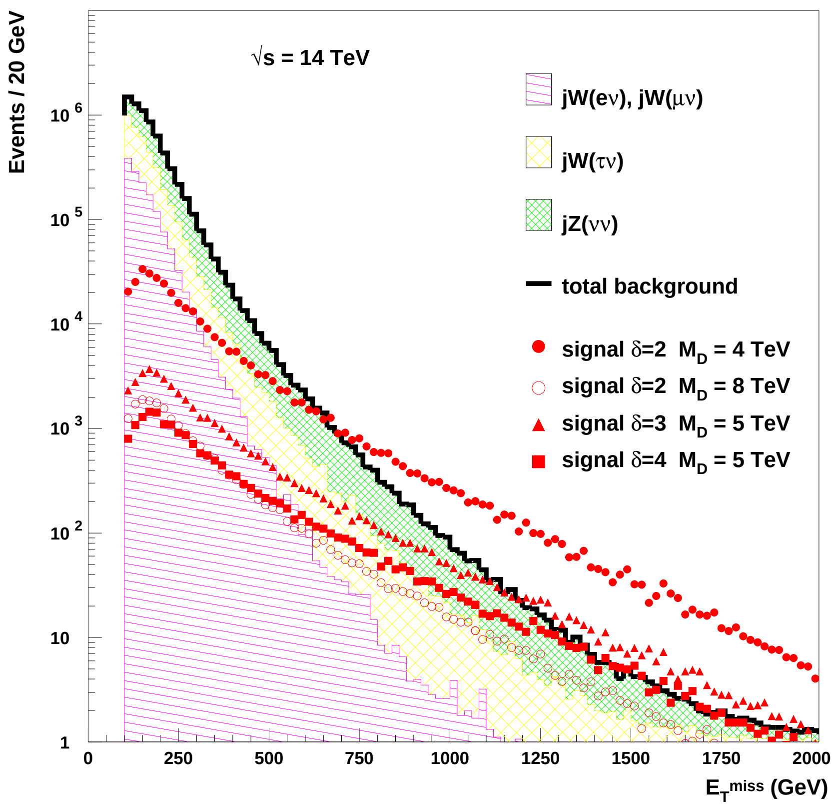
Gleisberg,Krauss,KM,... hep-ph/0306182



Missing energy signal at LHC

- The missing energy spectrum at the LHC for 100 fb^{-1}

Hinchliffe, Vacavant



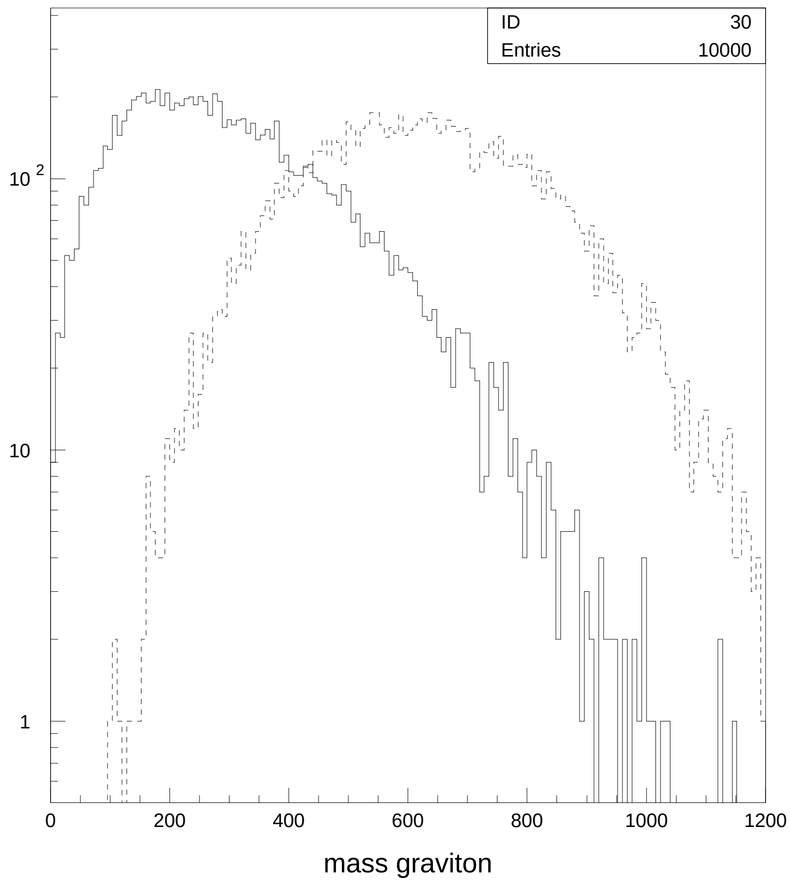
- $M_D < 6$ TeV can be discovered for $n = 2, 3, 4$. But which one is it?

- Instrumental backgrounds? (the Tevatron experience)

Missing graviton mass

- The missing mass spectrum is distinctive...

Lykken,KM,Spiropulu

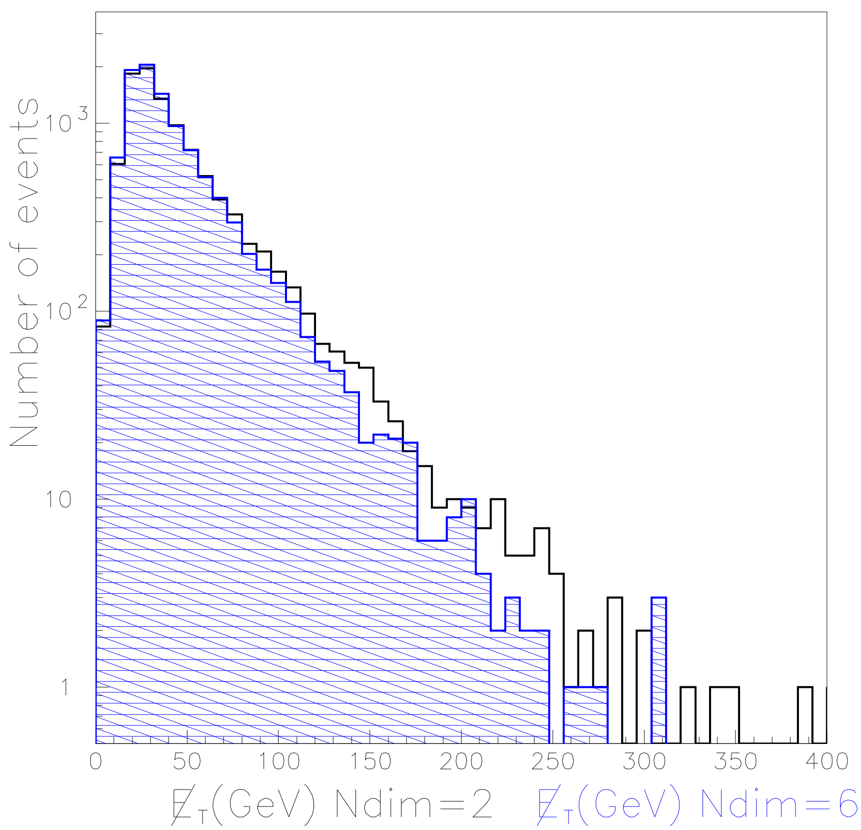


...but cannot be measured.

Missing energy spectrum

- Once normalized, appears identical for any n.

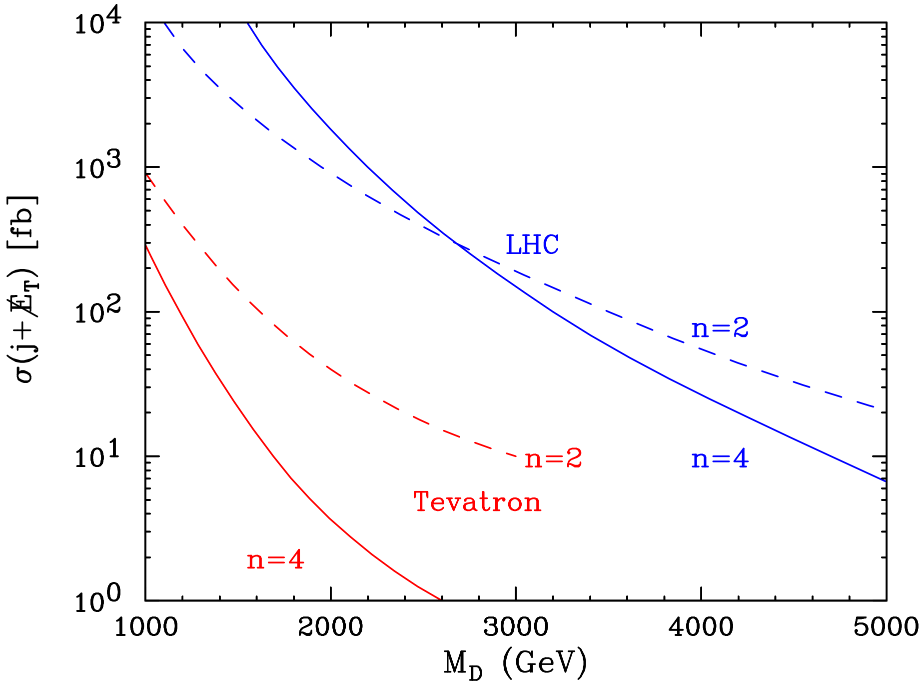
Lykken,KM,Spiropulu



How many extra dimensions?

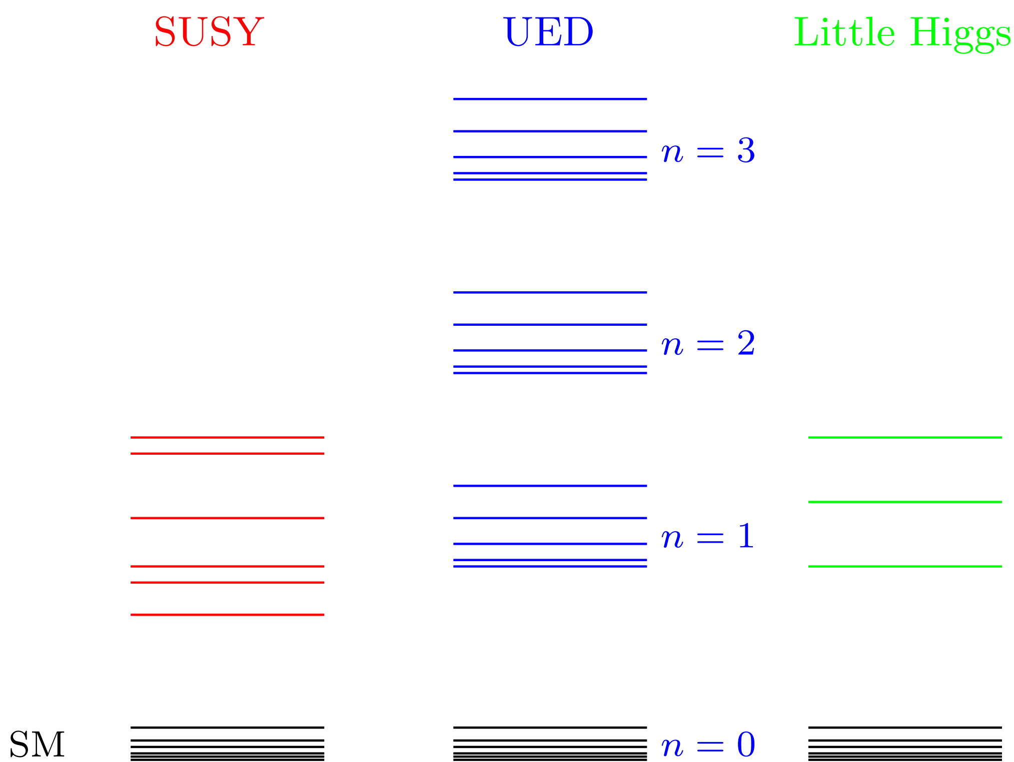
- The importance of being “low energy”!
- Need measurements at two different $\sqrt{s}$:

Giudice,Rattazzi,Wells



- Due to the different energy dependence of gg, gq and qq, the combined measurements at the Tevatron and the LHC may determine n.

An annoying proliferation of models



	SUSY	UED	Little Higgs
DM particle	LSP	LKP	LTP
Spin	1/2	1	0
Symmetry	R-parity	KK-parity	T-parity
Mass range	50-200 GeV	600-800 GeV	400-800 GeV

Supersymmetry

- Supersymmetry is an extra dimension theory with new anticommuting coordinates θ_α:

$$\Phi(x^\mu, \theta) = \phi(x^\mu) + \psi^\alpha(x^\mu)\theta_\alpha + F(x^\mu)\theta^\alpha\theta_\alpha$$

- SUSY relates SM particles and their superpartners ($\phi \leftrightarrow \psi$)
  - quarks, leptons $\Leftrightarrow$ squarks, sleptons
  - gauge bosons: g, $W^\pm$, W_3^0, B^0 $\Leftrightarrow$ gauginos: $\tilde{g}$, $\tilde{w}^\pm$, $\tilde{w}^0$, $\tilde{b}^0$
  - Higgs bosons: h^0, H^0, A^0, $H^\pm$ $\Leftrightarrow$ higgsinos: $\tilde{h}^\pm$, $\tilde{h}_u^0$, $\tilde{h}_d^0$
  - graviton: G $\Leftrightarrow$ gravitino: $\tilde{G}$
- The superpartners have
  - spins differing by 1/2
  - identical couplings
  - unknown masses (model-dependent)
- Discovering new particles with those properties IS discovering supersymmetry
- The superpartners are charged under a conserved R-parity
  - SM particles: $R = +1$
  - superpartners: $R = -1 \Longrightarrow$ stable LSP (DM?).
- No tree-level contributions to precision EW observables

Universal Extra Dimensions

Appelquist, Cheng, Dobrescu, hep-ph/0012100

- Universal Extra Dimensions is an extra dimension theory with new bosonic coordinates y (spanning a circle of radius R):

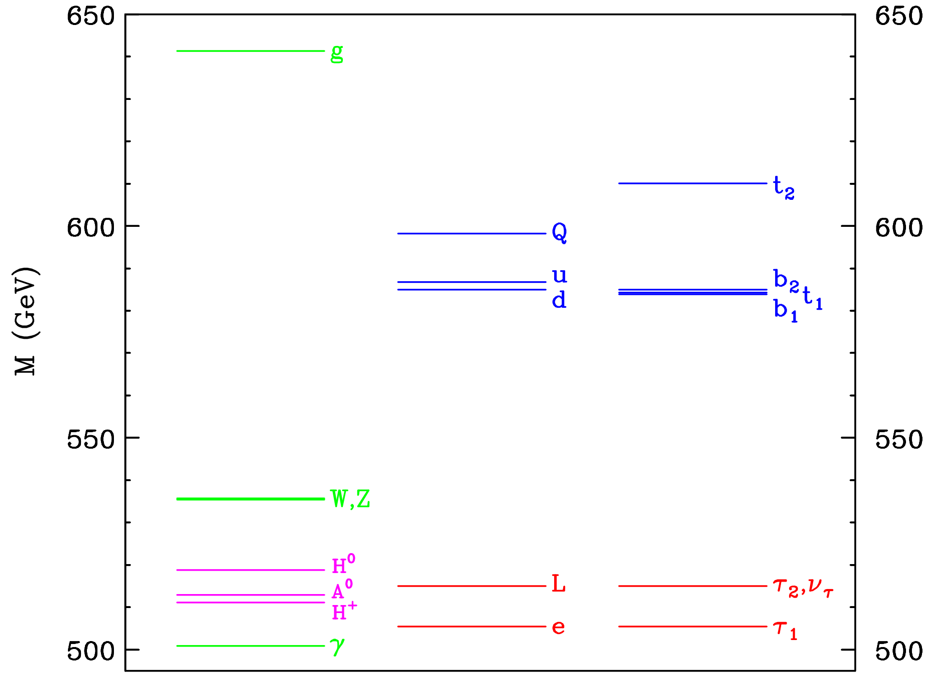
$$\Phi(x^\mu, y) = \phi(x^\mu) + \sum_{i=1}^{\infty} \phi^n(x^\mu)\cos(ny/R) + \chi^n(x^\mu)\sin(ny/R)$$

- Each SM field ϕ ($n = 0$) has an infinite tower of Kaluza-Klein (KK) partners ϕ^n and χ^n with
  - identical spins
  - identical couplings
  - unknown masses of order n/R
- Remnant of p_5 conservation: KK-parity $(-1)^n$
  - $KK = +1$ for even n and $KK = -1$ for odd n.
  - lightest KK partner at level 1 (LKP) is stable.
    $P_3 \to P_3' P_0, P_2 P_1, P_1 P_0$;
    $P_2 \to P_2' P_0, P_1 P_1, P_0 P_0$;
    $P_1 \to P_1' P_0$.
- No tree-level contributions to precision EW observables

UED spectrum at level 1

- Including radiative corrections, the mass spectrum of level 1 KK modes looks something like this:

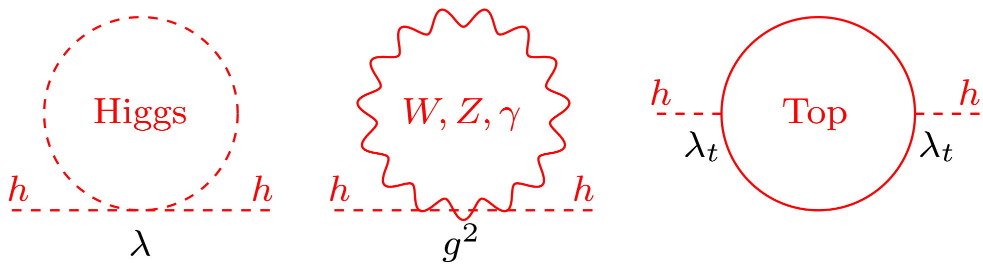
Cheng, KM, Schmaltz



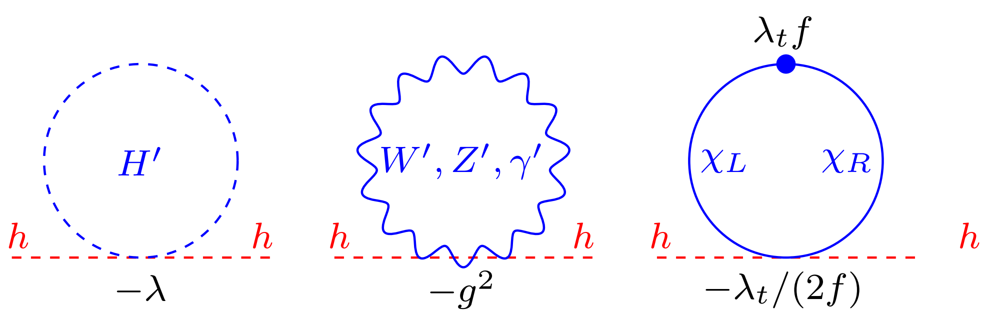
- Mimics supersymmetry!
- Seems challenging: “degenerate SUSY”?
- $W_1^\pm$, Z_1 have pure leptonic branchings!
- $\sin^2\theta_W^1 \approx 0 \Longrightarrow \gamma^1 \approx B^1$, similar to $\tilde{B}$ in SUSY.

Little Higgs models

- The hierarchy problem in the SM



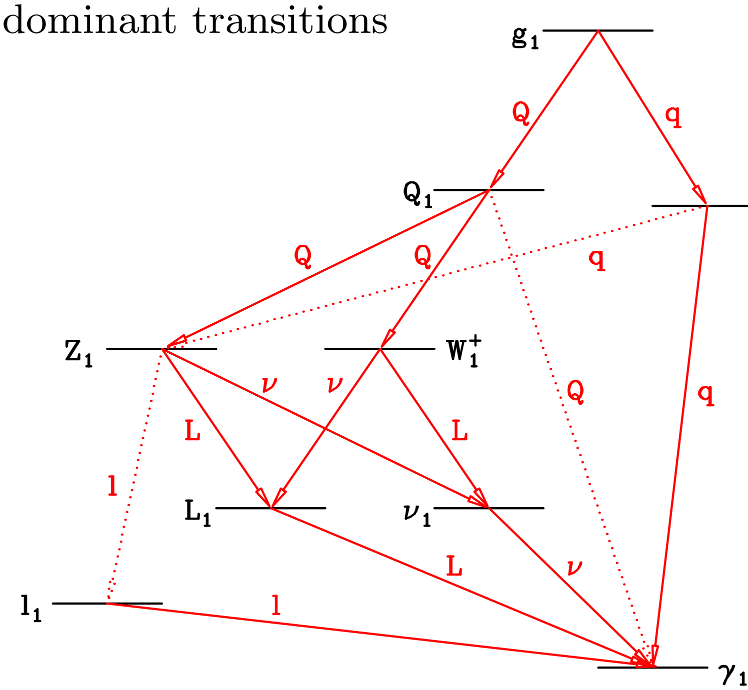
- Introduce new particles at TeV scale to cancel the one-loop quadratic divergences



- Conserved T-parity (Cheng, Low hep-ph/0308199)
  - $T = +1$ for SM particles, $T = -1$ for new particles.
  - the lightest T-odd particle is stable.
- No tree-level contributions to precision EW observables

Collider phenomenology of UED

- Allowed dominant transitions



- KK gluon: $B(g_1 \to Q_1 Q_0) \simeq B(g_1 \to q_1 q_0) \simeq 0.5$.
- SU(2)-singlet KK quarks: preferentially $q_1 \to \gamma_1 q_0$
- SU(2)-doublet KK quarks: preferentially to W_1 and Z_1
- KK W- and Z-bosons: only leptonic decays!
- KK leptons: 100% directly to the LKP.
- At hadron colliders we want: strong production, weak decays!
- This is Tevatron friendly!
- Essentially only 1 parameter (R^{-1}).

UED signature: $4\ell \not{E}_T$

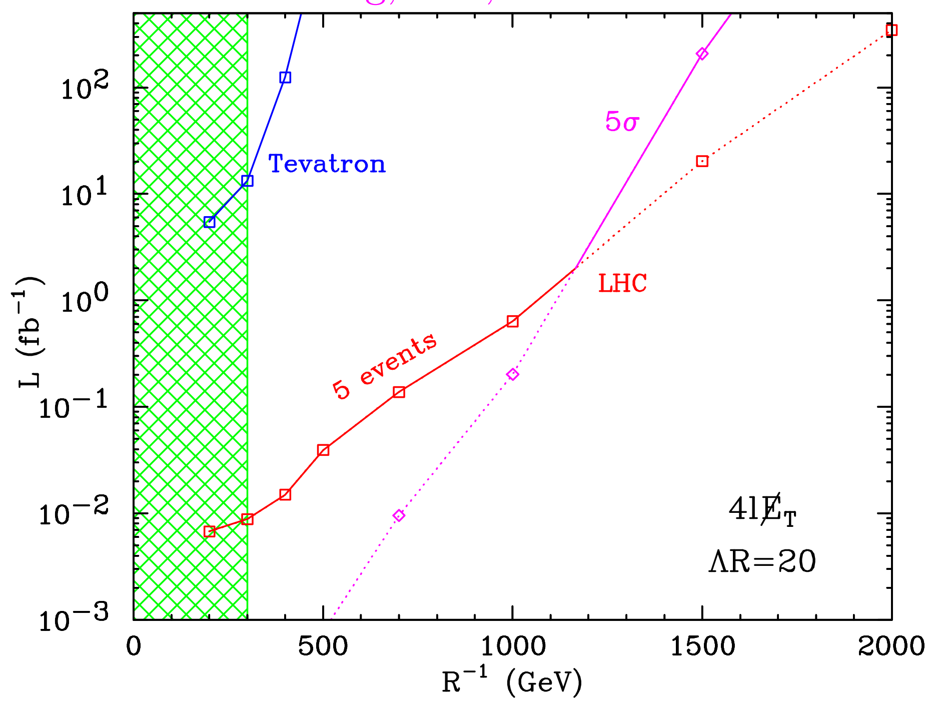
- Arises from inclusive $Q_1 Q_1$ production: $Q_1 \to Z_1 \to \ell^\pm \ell^\mp \gamma_1$
- Tevatron triggers
  - Single lepton $p_T(\ell) > 20$ GeV, $\eta(e) < 2.0$, $\eta(\mu) < 1.5$.
  - Missing energy $\not{E}_T > 40$ GeV.
- Tevatron cuts
  - $p_T(\ell) > \{15, 10, 10, 5\}$ GeV, $|\eta(\ell)| < 2.5$.
  - $\not{E}_T > 30$ GeV.
  - Invariant mass of OS, SF leptons: $|m_{\ell\ell} - M_Z| > 10$ GeV, $m_{\ell\ell} > 10$ GeV.
- Main background: $ZZ \to \ell^\pm \ell^\mp \tau^+ \tau^- \to 4\ell \not{E}_T$. Not a problem.
- LHC cuts (pass the single lepton trigger)
  - $p_T(\ell) > \{35, 20, 15, 10\}$ GeV, $|\eta(\ell)| < 2.5$.
  - $\not{E}_T > 50$ GeV.
  - Invariant mass of OS, SF leptons: $|m_{\ell\ell} - M_Z| > 10$ GeV, $m_{\ell\ell} > 10$ GeV.
- LHC backgrounds: multi-boson, ttZ, fakes, etc.

Assumption: 50 events/year (100 fb^{-1}).

UED discovery reach at the Tevatron and LHC

- Discovery reach in the $Q_1 Q_1 \to 4\ell \not{E}_T$ channel.

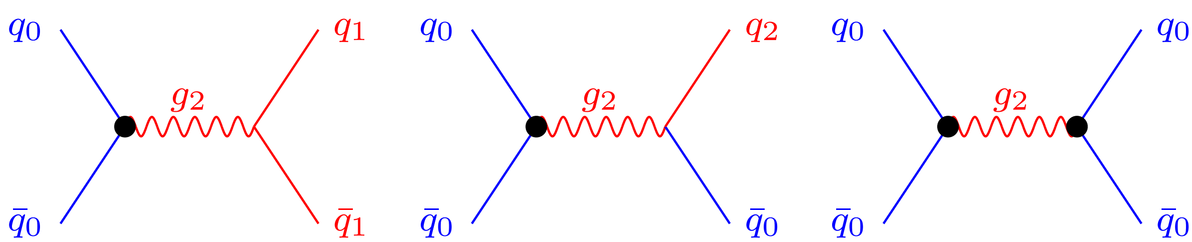
Cheng, KM, Schmaltz



- Typical signatures include:
  - soft leptons, soft jets, not a lot of $\not{E}_T$
  - a lot of missing mass (HC can't measure it)
- $B(Q_1 \to 2\ell \not{E}_T + X) \sim \frac{1}{9}$. In principle, channels with W_1's can also be used – less leptons, but larger BR's. Homework?
- We did not make use of the jets

Bosonic or fermionic supersymmetry?

- Can you tell SUSY from UED?
- Look for the higher KK levels: e.g. g_2 resonance.



$\sim 55\%$ $\sim 35\%$ $\sim 10\%$

- g_2 appears a high mass dijet resonance. Z'?
- Z_2, γ_2 appear as high mass dijet or dilepton resonances.
- Recycle existing LHC analyses for Z' searches
- Reach for R^{-1} in GeV with 100 fb^{-1} (Datta,Kong,KM)

KK mode	jj	$\mu^+\mu^-$	e^+e^-
g_2	350	NA	NA
Z_2	worse	570	600
γ_2	worse	570	600

- Can we discriminate the Z_2 and γ_2 resonances?
- Confusion: Supersymmetry plus one or more Z'?

Bosonic or fermionic supersymmetry?

- Measure the spins! Need something like COMPHEP. Why?
  - Spin correlations accounted for.
  - Automated: ideal for new models which are straightforward generalizations of the Standard Model (UED, little Higgs).
  - Once the Feynman rules are defined, any final state signature ($n < 5$) can be studied.
  - It already has SUSY.
  - It is interfaced to PYTHIA.
  - The experimentalists know how to deal with it.
- UED implementation in COMPHEP
  - Level 1 and 2 are both fully implemented with the correct 1-loop masses and widths.

SUSY versus UED at a LC

- The spin information is encoded in the angular distributions!

SUSY

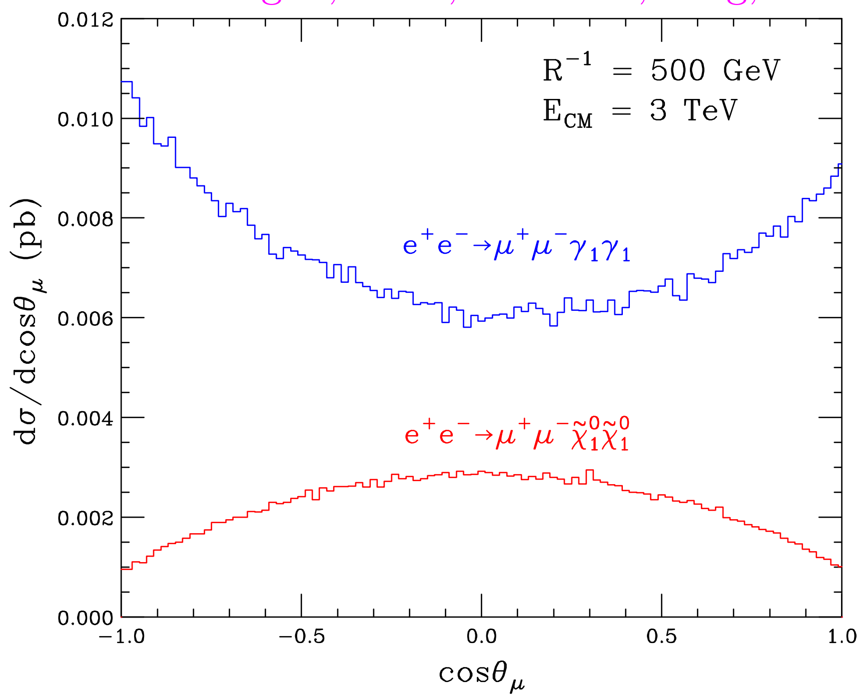
$$e^+e^- \to \tilde{\mu}^+\tilde{\mu}^- \to \mu^+\mu^-\tilde{\chi}_1^0\tilde{\chi}_1^0$$

UED

$$e^+e^- \to \mu_1^+\mu_1^- \to \mu^+\mu^-\gamma_1\gamma_1$$

$$\frac{d\sigma}{d\cos\theta} \sim 1 - \cos^2\theta \qquad \frac{d\sigma}{d\cos\theta} \sim 1 + \cos^2\theta$$

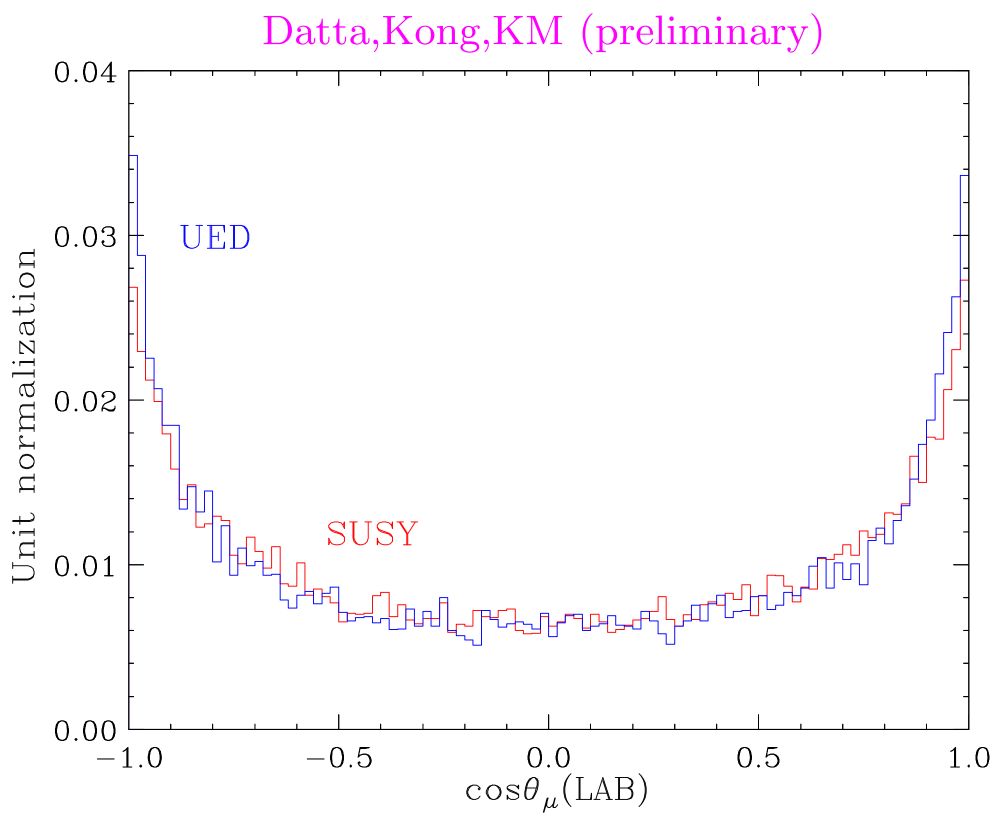
Battaglia,Datta,De Roeck,Kong,KM



- Significant difference in the total cross-section as well!
- The masses can be extracted from the E_μ distribution.
- Threshold scan would confirm the spins.

Spin determination at the LHC

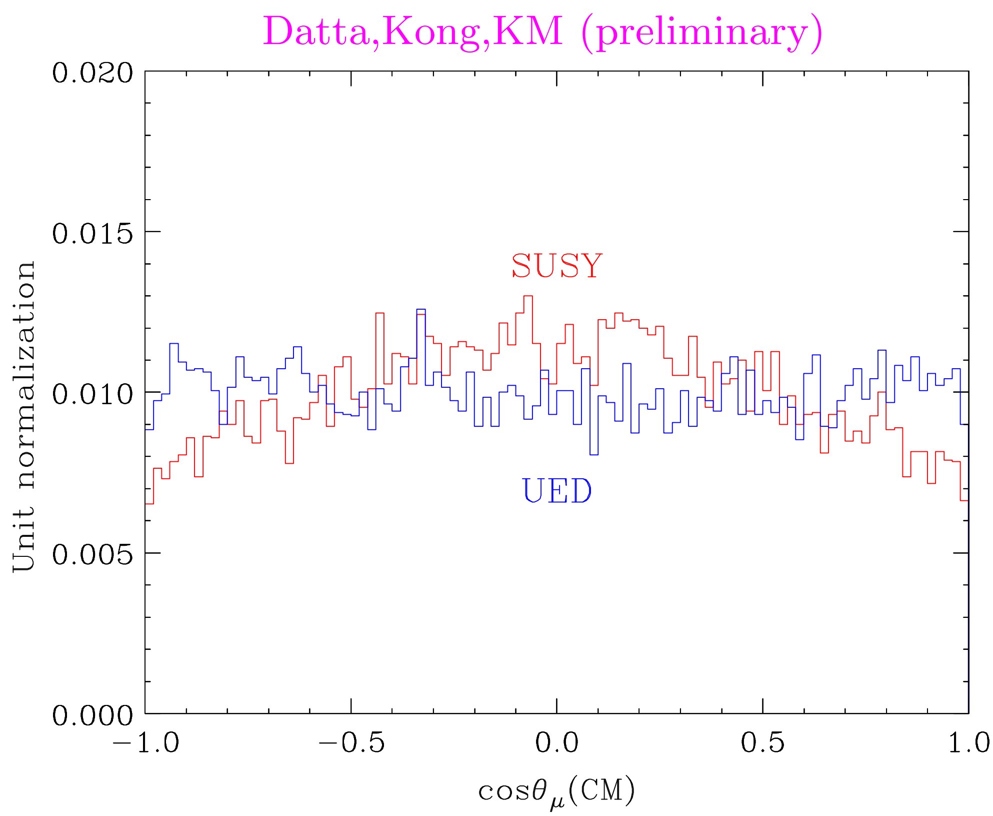
- If we simply do the same trick, it doesn't work:



- We need to somehow account for the LAB-to-CM boost.
- Toy study (ignore backgrounds).

Spin determination at the LHC

- The best possible case: perfect reconstruction of the boost in each event (a cheat).



- Surprise: it's already worse than the LC case, the UED distribution is flat:

$$\frac{d\sigma}{d\cos\theta} \sim 1 + \frac{E^2 - m^2}{E^2 + m^2}\cos^2\theta \sim 1$$

because the KK-muons are produced near threshold: $E \sim m$.

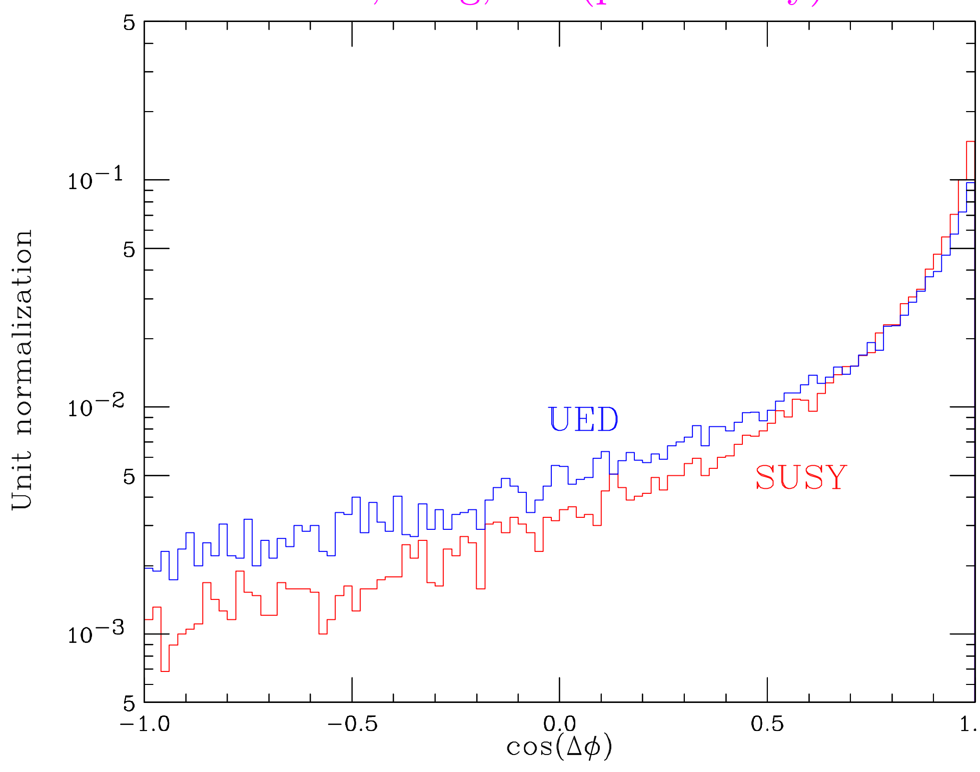
The large boost approximation

- OK, we can't know the boost exactly, how about an approximation:

$$\Delta\phi(\vec{P}_\mu, \vec{P}_{LKP}) \approx 0$$

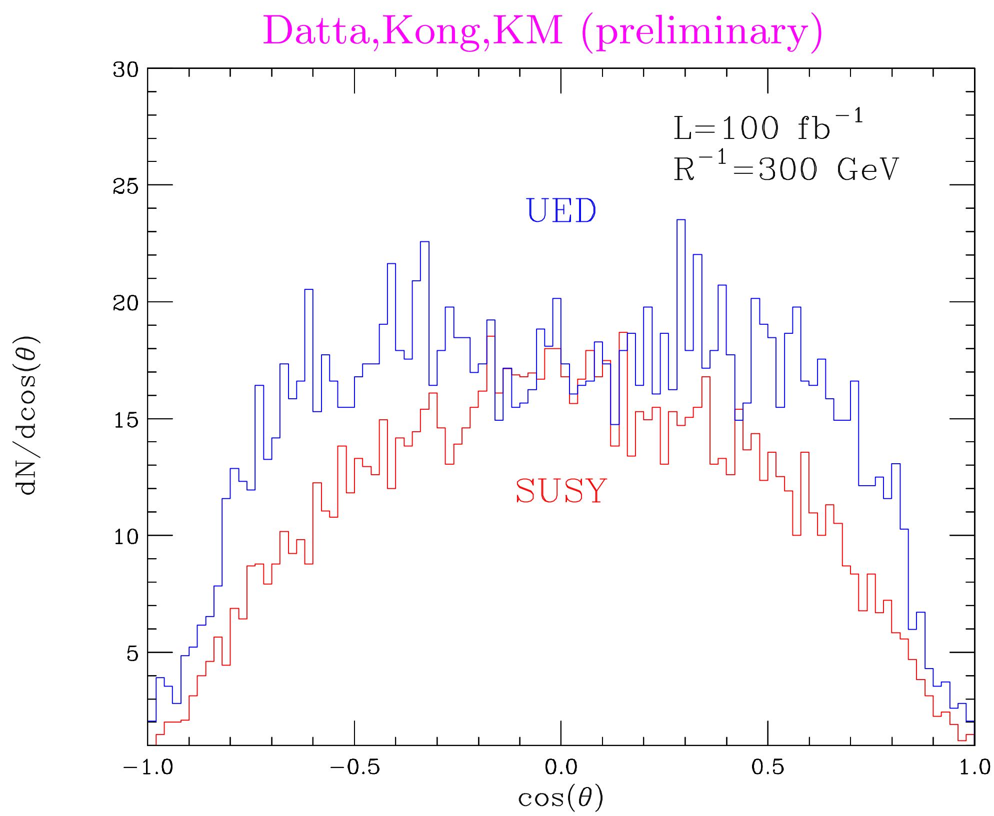
- Does it work?

Datta,Kong,KM (preliminary)



SUSY versus UED at the LHC

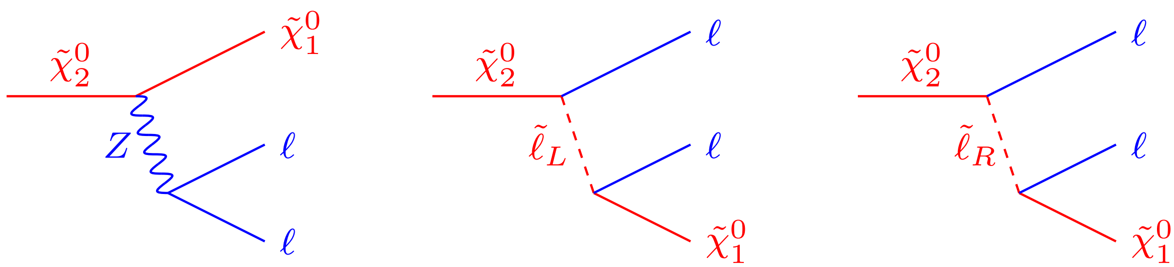
- Cuts:
  - $E_{\mu^+} + E_{\mu^-} > 40$ GeV (similar with 60 and 80 GeV).
  - $|\eta(\mu)| < 2.5$.
- We can recover to some extent the difference in shapes!



- Backgrounds? Other tricks? Strong KK production?

Precision measurements?

- Typically there is little SM background
- What information is contained in $m_{\ell\ell}$?
- The decay is mediated by several diagrams:



- Consider several cases
  - On-shell Z
  - On-shell slepton (slepton discovery?)

$$(m_{\ell\ell})_{max} = \frac{\sqrt{(M^2_{\tilde{\chi}_2^0} - M^2_{\tilde{\ell}})(M^2_{\tilde{\ell}} - M^2_{\tilde{\chi}_1^0})}}{M_{\tilde{\ell}}}$$

  - Off-shell slepton (sensitivity to the slepton mass?)

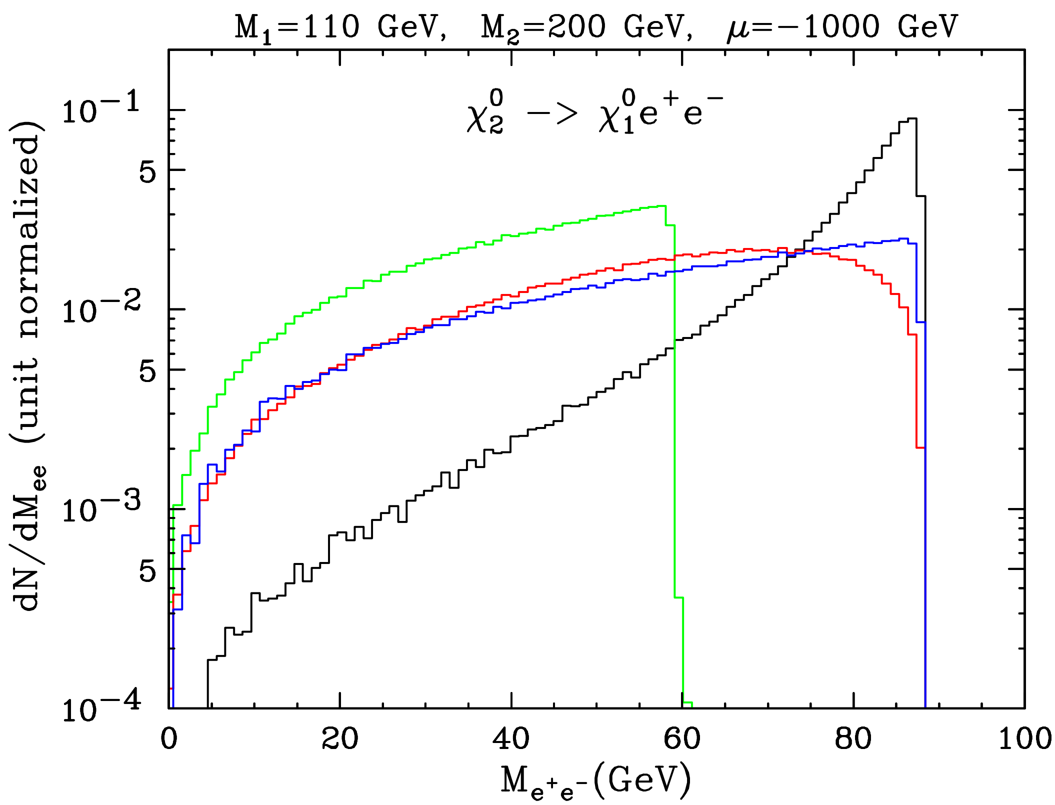
$$(m_{\ell\ell})_{max} = M_{\tilde{\chi}_2^0} - M_{\tilde{\chi}_1^0}$$

- Notice that $M_{\tilde{\ell}} = \sqrt{M_{\tilde{\chi}_1^0} M_{\tilde{\chi}_2^0}}$ has the same edge as $M_{\tilde{\ell}} = \infty$.

Dilepton mass distribution at LHC

- There is information in the shape of the distribution!

Birkedal,Group,KM

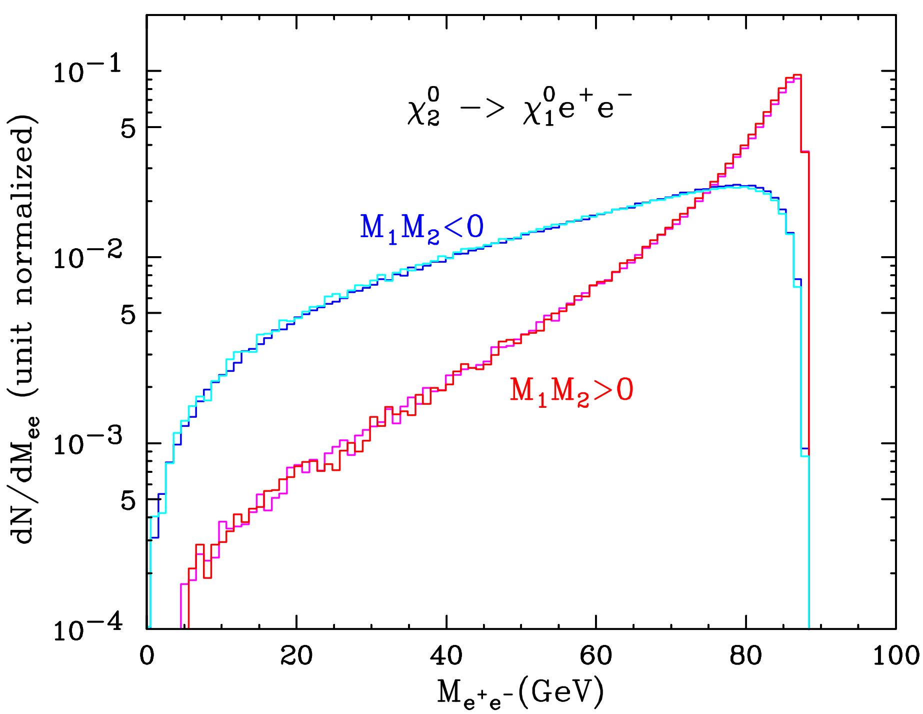


- Off-shell Z only, $M_{\tilde{\ell}_L} = M_{\tilde{\ell}_R} = \infty$. (FP,SS)
- On-shell $M_{\tilde{\ell}_R} = 120$ GeV.
- On-shell $M_{\tilde{\ell}_R} = \sqrt{M_{\tilde{\chi}_1^0} M_{\tilde{\chi}_2^0}}$.
- Off-shell $M_{\tilde{\ell}_R} = 300$ GeV only.

Dilepton mass distribution at LHC

- The distribution is also sensitive to
  - The relative sign (phase) of M_1 and M_2: compare $M_1 M_2 < 0$ to $M_1 M_2 > 0$.
  - The absolute mass scale: compare $M_1 = 110$ GeV to $M_1 = 300$ GeV.
- Only the off-shell Z diagram again:

Birkedal,Group,KM



- There will be more in the data than the TDR's say!

Lessons

- Think big! (Discoveries, new tricks...)
- Think small! (Low integrated luminosity...)
- Think new physics signatures and what a potential discovery would tell you.
- The complementarity of the Tevatron and the LHC
- Advice to the experimentalists: make a wish list and present it to us during this Workshop.
- Advice to the theorists: make those wishes come true!